ARTICLE IN PRESS

Waste Management xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Review

Food-waste-to-energy conversion technologies: Current status and future directions

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ARTICLE INFO

Article history:
Received 8 June 2014
Accepted 9 December 2014
Available online xxxx

Keywords:
Food waste
Anaerobic digestion
Fermentation
Incineration
Gasification
Hydrothermal carbonization

ABSTRACT

Food waste represents a significantly fraction of municipal solid waste. Proper management and recycling of huge volumes of food waste are required to reduce its environmental burdens and to minimize risks to human health. Food waste is indeed an untapped resource with great potential for energy production. Utilization of food waste for energy conversion currently represents a challenge due to various reasons. These include its inherent heterogeneously variable compositions, high moisture contents and low calorific value, which constitute an impediment for the development of robust, large scale, and efficient industrial processes. Although a considerable amount of research has been carried out on the conversion of food waste to renewable energy, there is a lack of comprehensive and systematic reviews of the published literature. The present review synthesizes the current knowledge available in the use of technologies for food-waste-to-energy conversion involving biological (e.g. anaerobic digestion and fermentation), thermal and thermochemical technologies (e.g. incineration, pyrolysis, gasification and hydrothermal oxidation). The competitive advantages of these technologies as well as the challenges associated with them are discussed. In addition, the future directions for more effective utilization of food waste for renewable energy generation are suggested from an interdisciplinary perspective.

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1. Introduction

As of 2011, the world has generated an estimated 2 billion tons of municipal solid waste (MSW) (Amoo and Fagbenle, 2013). The amount of MSW generated is expected to grow much higher due to rapid urbanization, industrialization and population growth, which is projected to reach 9.5 billion by 2050 (FAO, 2009). According to Intergovernmental Panel on Climate Change (IPCC, 2006), food waste makes a dominant contribution to MSW (25–70%), which is composed of plastic, metal, glass, textiles, wood, rubber, leather, paper, food waste and others with the exception of

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http://dx.doi.org/10.1016/j.wasman.2014.12.004
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Please cite this article in press as: Pham, T.P.T., et al. Food-waste-to-energy conversion technologies: Current status and future directions. Waste Management (2014), http://dx.doi.org/10.1016/j.wasman.2014.12.004

industrial waste (Fig. 1). About 1.3 billion tons, one third of the food produced in the world for human consumption annually, are lost or wasted throughout the supply chain, from production to consumption (FAO, 2011). Food waste in a food supply chain can be sub-categorized into pre-consumer (e.g. wastes generated from agriculture, processing and distribution) and post-consumer wastes (e.g. wastes from meal preparation and consumption) (Pfaltzgraff et al., 2013). The National Resources Defense Council (NRDC, 2012) has recently estimated that approximately 40% of food produced in the United States of America is lost in the form of waste during its processing and distribution by retailers, restaurants and consumers. The United Kingdom and Japan also follow a similar trend, discarding between 30% and 40% of their food produced every year (Kosseva, 2009). In South Africa, food waste generation was estimated to be 9 million tons per annum (Oelofse and Nahman, 2013). Singapore, a highly populated, industrialized city, produced 542,720 tons of food waste in 2006 and reached about 703,200 tons in 2012 according to Singapore's National Environmental Agency (NEA, 2012). In the European Union, food garbage is expected to increase from 89 million tons in 2006 to 126 million tons in 2020 (European Commission, 2010). Every year the European food-processing industry produces vast volumes of aqueous wastes. These wastes are composed of fruit and vegetable residues and discarded items, molasses and bagasse from sugar refining, bones, flesh and blood from meat and fish processing, stillage and other residues from wineries, distilleries, and breweries, dairy wastes such as cheese whey, and wastewaters from washing, blanching, and cooling operations (Kosseva, 2011). Many of these wastes contain low levels of suspended solids and low concentrations of dissolved materials, which cause not only visual discomfort by producing different moldering gases and offensive odors, but also cause adverse environmental impacts due to leaching in landfill sites. These wastes lead to a waste of resources used in food production and distribution, including land, water, energy, fertilizers, pesticides, labor and capital. Currently, most of food wastes are recycled, mainly as animal feed and compost (Lin et al., 2013). The remaining quantities are incinerated and disposed off in landfills, causing serious emissions of methane (CH_4), which is 23 times more potent than carbon dioxide (CO_2) as a greenhouse gas and significantly contributes to climate change.

Apart from the environmental challenges posed, the inherent complexity of food waste composition makes it a very attractive source of value-added products. Most of the materials generated as wastes by the food-processing industries contain components that could be utilized as substrates and nutrients in a variety of microbial/enzymatic processes. Joshi (2002) and Marwaha and Arora (2000) discussed the value-added products actually produced from food industry wastes, or potentially so, which include animal feed, single-cell protein and other fermented edible products, baker's yeast, organic acids, amino acids, enzymes (e.g., lipases, amylases, and cellulases), flavors and pigments, the biopreservative bacteriocin (from the culture of *Lactococcus lactis* on cheese whey), and microbial gums and polysaccharides.

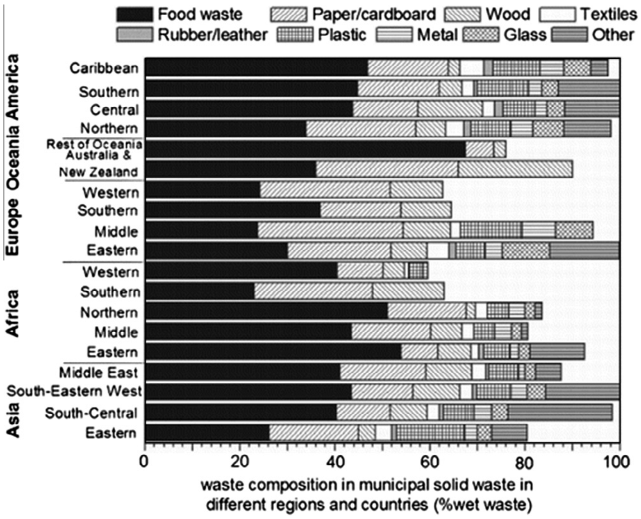

Fig. 1. The percentage of different waste types in municipal solid waste in different regions and countries (reproduced from IPCC, 2006).

In recent years, it has been recognized that food waste is an untapped resource with great potential for generating energy. Thus, energy recovery from food waste is an additional attractive option to pursue, particularly from the energy security viewpoint. This realization has motivated fundamental research on technologies that help to recover some valuable fuels from food waste to reduce the environmental burden of its disposal, avoid depletion of natural resources, minimize risk to human health and maintain an overall balance in the ecosystem. Although there has been a considerable amount of research focused on the conversion of food waste to renewable energy, there is a lack of comprehensive reviews of the published literature. McKendry (2002) reviewed various biomass-to-energy conversion technologies, but there was no specific emphasis on the use of food wastes as feedstocks.

In the current review, we provide insights into various technologies that have been explored for food-waste-to-energy conversion including biological (e.g. anaerobic digestion and fermentation), thermal and thermochemical technologies (e.g. incineration, pyrolysis, gasification and hydrothermal oxidation) (Fig. 2). This review discusses the advantages as well as the major challenges associated with these technologies. In the light of recent technological advances and the drive towards using food waste as a raw material to both reduce the environmental burden of its disposal and address the concerns about future resources, this review identifies key knowledge in food-waste-to-energy conversion technologies. In addition, we suggest future directions for more effective ways of treating food waste for renewable energy generation from the resource recovery viewpoint.

2. Current technologies for energy generation from food waste

2.1. Biological technology

2.1.1. Anaerobic digestion

Anaerobic digestion (AD) of organic wastes in landfills produces biogas comprising mainly CH_4 and CO_2, and traces amounts of other gases such as nitrogen (N_2), oxygen (O_2) and hydrogen sulfide (H_2S) that escape into the atmosphere and pollute the environment (Zhu et al., 2009). Under controlled conditions without oxygen, the same process has the potential to convert the organic wastes into useful products such as biofuels (e.g. biogas) and nutrient enriched digestates which can be used as soil conditioners or fertilizers (Chanakya et al., 2007; Guermoud et al., 2009). With the introduction of both commercial and pilot AD plant designs during early 1950s, AD of organic wastes has received worldwide attention (Karagiannidis and Perkoulidis, 2009). AD has many environmental benefits including the production of a renewable energy platform, the possibility of nutrient recycling, and the reduction of waste volumes (Kosseva, 2011).

It was reported that 1 m^3 of biogas from AD is equivalent to 21 MJ of energy, and it could generate 2.04 kW h of electricity considering the 35% of generation efficiency (Murphy et al., 2004). However, the major problem is the long duration of the microbial reaction, which is generally in the range of 20–40 days (Table 1). Also, the high concentration of free ammonia (NH_3) resulting from

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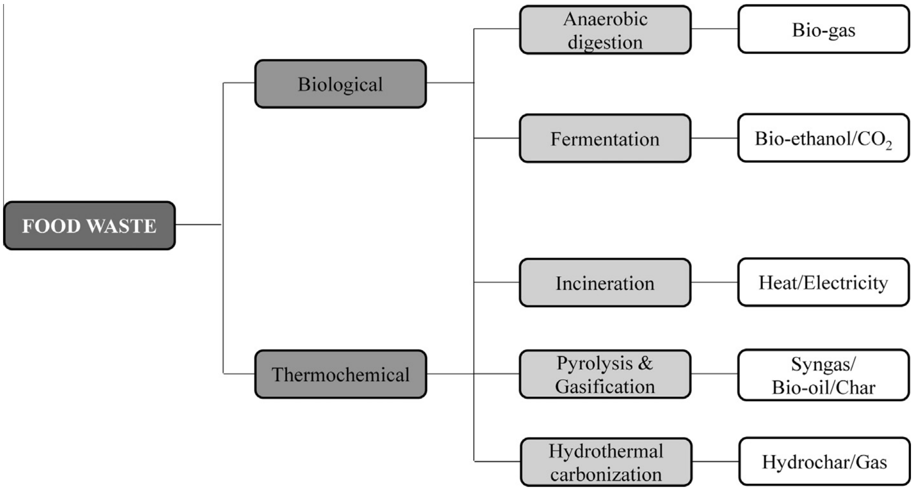

Fig. 2. Summary of food-waste-to-energy technologies.

Table 1
Operational and performance data of anaerobic digestion of food waste.

Substrate	Co-substrate	Bioreactor type	Temp. (°C)	OLR (kg VS m^{-3} day^{-1})	HRT (days)	CH_4 yield (m^3 kg^{-1} VS)	Biogas yield (m^3 kg^{-1} VS)	%CH_4	Energy content (MJ/m^3)	References
Potato waste	NA/Beet leaves	Batch (0.5 L)	37	NR	14	0.42/0.68	NR	62/84	23.1/31.3	Parawira et al. (2004)
Potato processing waste	NA	CSTR	55	0.8–3.4	NR	NR	0.65–0.85	58	21.6	Linke (2006)
FVW	NA	Tubular reactor (18 L)	35	6% TS	20	NR	0.707	57	21.3	Bouallagui et al. (2003)
FVW	NA	2-phase system (18 L)	35/55	7.5 kg COD	20	NR	0.705/0.997	64/61	23.9/22.6	Bouallagui et al. (2005)
Food waste	NA	Batch system	50	6.8/10.5	10/28	0.348/0.435	NR	73	27.2	Zhang et al. (2007)
Food waste	NA	Batch system	35	NR	20–60	NR	0.49	NR	NA	Forster-Carneiro et al., (2008a)
FVW	NA/ Abattoir waste	ASBR (2 L)	55	1.24/2.56	20	NR	0.48/0.73	60/62	22.4/23.1	Bouallagui et al. (2009)
FVW	SW, manure	Semi cont. (2 L)	35	1.3	30	0.32	1.36	56	20.9	Alvarez and Lidén, (2008)
Food waste	NA	3-stage semi cont.	50	NR	12.4	NR	NR	67.4	25.1	Kim et al. (2006b)
Food waste	NA	Batch (1.1 L)	55	NR	90	0.18	NR	NR	NA	Forster-Carneiro et al. (2008b)

FVW fruit and vegetable wastes, *SW* slaughter house waste, *CSTR* continuous stirred tank reactor, *ASBR* anaerobic sequencing batch reactor, *Semi cont.* semi-continuous, *Temp.* temperature, *OLR* organic loading rate, *VS* volatile solids, *HRT* hydraulic retention time, *COD* chemical oxygen demand, *NR* not reported, *NA* not applicable, energy content of methane 37.3 MJ/m^3 (Zhang et al., 2007).

degradation of nitrogen rich protein components can prove toxic to the specific activity of methanogenic bacteria, causing serious effects to the AD process (Chen et al., 2008; Fountoulakis et al., 2008). Food wastes consist mostly of organic components making the AD a good choice for alternative energy generation. However, high salt concentrations in food waste inhibit AD due to the presence of cations such as sodium, potassium, calcium, and magnesium (Chen et al., 2008). To address this issue, co-digestion of food waste with low nitrogen and lipid content waste is preferably used to decrease the concentration of nitrogen, thus reducing problems associated with the accumulation of intermediate volatile compounds and high NH_3 concentrations (Castillo et al., 2006). Interestingly, it was observed that anaerobic co-digestion of sewage sludge and highly rich organics such as food wastes could increase the CH_4 yield in biogas (Gómez et al., 2006; Kabouris et al., 2009). Several studies have shown that co-digestion of food waste and municipal waste helps to improve the biogas yield up to 40–50% compared to the digestion of food waste alone (Table 1). Parawira et al. (2004) conducted batch anaerobic co-digestion under mesophilic conditions at a hydraulic retention time (HRT) of 14 days with different combinations of potato waste and sugar beet leaves. They reported an enhanced yield of 0.68 m^3 CH_4 kg^{-1} volatile solid (VS) added with a mixing ratio of (24:16% total solid), and another yield of 0.42 m^3 CH_4 kg^{-1} VS added from potato waste alone. Bouallagui et al. (2009) used abattoir wastewater as a co-substrate in AD of fruit and vegetable waste (FVW). They observed a VS removal between 73% and 86% and a biogas yield of about 0.3–0.73 m^3 kg^{-1} VS added at organic loading rates (OLRs) up to 2.56 kg VS m^3 day^{-1} in the anaerobic sequencing batch reactor. Also, it is reported that the addition of abattoir wastewater to the feedstock enhanced biogas yield up to 51.5%. Yan et al. (2014) observed that rumen microbes from cow manure enhanced hydrolysis of food waste in acidogenic leach-bed reactor, subsequently increased methane yields in methanogenesis. In another study, Alvarez and Lidén (2008) examined a semi-continuous mesophilic anaerobic treatment in an experiment using combinations of solid slaughterhouse waste, FVW, and manure in a co-digestion process. Anaerobic co-digestion resulted in CH_4 yields of 0.3 m^3 -

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Table 2
Pretreatment process of food waste in anaerobic digestion.

Pretreatment method	Processes	Pretreatment condition	Type of AD system	Results	References
Physical pretreatment	Mechanical	Size reduction by beads mill	Mesophilic batch	40% higher COD solubilization and 28% higher biogas production	Izumi et al. (2010)
	High pressure	Pressurized until 10 bar and depressurized	Thermophilic batch	12 ± 7% higher COD solubilization and 48% higher biogas production	Ma et al. (2011)
Thermal pretreatment	Microwave	Microwave with intensity of 7.8 °C/min	Mesophilic batch	24% higher COD solubilization and 6% higher biogas production	Marin et al. (2010)
	Thermochemical liquidization	175 °C, 4 MPa, 1 h	Mesophilic batch	33% higher in methane content of the produced biogas	Sawayama et al. (1997)
Chemical pretreatment	Dilute-acid hydrolysis	Addition of HCl until pH = 2	Thermophilic batch	13 ± 7% higher COD solubilization and 48% higher biogas production	Ma et al. (2011)
		Immersion in 1 M HCl for 30 days	Mesophilic batch	31% higher in methane yield	Kivaisi and Eliapenda (1994)
	Alkaline	Addition of $Ca(OH)_2$ up to pH 6.5 and of 10 g/L of bentonite	Mesophilic batch	91% removal of COD	Beccari et al. (2001)
Biological pretreatment	Enzymatic hydrolysis	Incubation with 0.1% enzyme mixture (carbohydrase:protease:lipase, ratio 1:2:1)	Mesophilic batch	3.3 times higher in hydrolysis rate of VSs in food waste for CH_4 production	Kim et al., (2006a)

kg^{-1} VS added, with CH_4 content between 54% and 56% at OLRs in the range 0.3–1.3 kg VS m^3 day^{-1}. They concluded that co-digestion of various waste types such as manure, solid slaughterhouse wastes and FVW in a mesophilic anaerobic process facilitates the possibility of treating the wastes, which cannot be successfully treated separately.

Among the factors affecting the mass transfer in each biological step of AD, both the pretreatment and the quality of the substrate used play a fundamental role. According to the different kinds of substrates, pretreatments such as physical, chemical, thermal and biological, can be used in order to optimize biological process yields. Pretreatment methods for food waste in AD are summarized in Table 2. Regarding the physical pretreatments, both mechanical and high pressuring machines are being widely used. As for thermal pretreatments, microwave devices are implemented to increase the yields (Neves et al., 2006). There were several studies into various pre-treatments, including those that were steam explosion (Nakamura and Sawada, 2003), thermochemical liquidization (Sawayama et al., 1997), and enzymatic hydrolysis (Kim et al., 2006a) to enhance the hydrolysis rate of VSs in food waste for CH_4 production. The alkaline pretreatment was also used as a pretreatment method in biogas production (Taherzadeh and Karimi, 2008). Olive mill effluent is an example of seasonal waste with low pH (about 4.3), and high lipid (ca. 13 g/L) and phenolic compounds concentration (ca. 8 g/L). Addition of lime and bentonite greatly improves the digestion of olive mill effluents with more than 91% removal of COD (Beccari et al., 2001). Dilute-acid hydrolysis is probably the most commonly applied method among the chemical pretreatment methods (Taherzadeh and Karimi, 2008). It can be used either as a pretreatment of lignocellulose for enzymatic hydrolysis, or as the actual method of hydrolyzing to fermentable sugars. Pretreatment of bagasse and coconut fibers with HCl improved the formation of biogas from these materials by 31% and 74%, respectively (Kivaisi and Eliapenda, 1994). In another study by Li et al. (2009) on Bermudagrass, reed and rapeseed for bioethanol production, pretreatment with phosphoric acid–acetone was reported to yield higher ethanol concentration.

Several types of bioreactors are currently applied for AD, but the three major systems commonly used include batch, continuous one-stage, and continuous two-stage reactors with a variety of methanizers. Some examples of these reactors are continuously stirred tank reactor (CSTR), tubular reactor, anaerobic sequencing batch reactor (ASBR), upflow anaerobic sludge blanket (UASB) and fixed film reactor (Bouallagui et al., 2005). Forster-Carneiro et al. (2008a) optimized the biomethanization procedure of food waste in six reactors with three different total solid (TS) concentrations (20%, 25%, and 30%) and two different inoculums dosages (20–30% of mesophilic sludge). The reactor with 20% TS and 30% of inoculums revealed to be the best performance of food waste treatment and CH_4 production with a high CH_4 yield of 0.49 m^3 kg^{-1} VS added between 20 and 60 days during the operation. According to Bouallagui et al. (2003), the maximum OLR for the mesophilic anaerobic digestion of FVW in a tubular reactor is 6% of TS with a high yield of 0.707 m^3 biogas kg^{-1} VS added for a 20-day HRT. Linke (2006) used the potato processing wastes as substrates for anaerobic biogas production in a continuous stirred tank reactor at thermophilic condition. They reported that an increase of the OLR in the range of 0.8–3.4 kg VS m^3 day^{-1} resulted in reduction of the biogas yield (Linke, 2006). In addition, biogas yields with its CH_4 composition were obtained to be 0.85–0.65 m^3 kg^{-1} VS and 58–50%, respectively. Bouallagui et al. (2009) observed a maximum OLR of 1.24 kg VS m^3 day^{-1} when they operated a thermophilic ASBR treating FVW at an HRT of 15 days. They achieved a high biogas output of 0.48 m^3 kg^{-1} VS added with 60% methane content and a 79% VS reduction. Kim et al. (2006b) examined the AD of food waste in a three-stage semicontiuous system at thermophilic condition. They obtained 67% CH_4 composition in the biogas with a 12.4-day HRT. Forster-Carneiro et al. (2008b) carried out a batch experiment to study the AD of shredded organic fraction of the MSW and food waste separately. As a result, the smallest VS removal (32%) and high CH_4 composition of 0.18 m^3 kg^{-1} VS added in the biogas were obtained for food waste. To determine the effect of HRT, Zhang et al. (2007) studied the AD of food waste in a batch system for 10 and 28 days. It was reported that the highest CH_4 yield of 0.435 m^3 kg^{-1} VS was obtained at the end of the 28-day digestion with VS removal of 81%, which is followed by 0.348 m^3 kg^{-1} VS at the end of 10-day digestion. The energy content of biogas derived from AD of food waste varied depending on experimental conditions and is summarized in Table 1. In a systematic analysis, Morris (1996) reported that an average of 12.7 kJ/g TS of food waste is produced from AD. Energy balance for a full-scale food waste digester showed the potential recoverable energy was 1462 kW h per ton TS of food waste and biogas production was 642 m^3 ton^{-1} VS added with 62% methane content (Banks et al., 2011). These results showed evidences that food waste is a good alternative feedstock for AD because of its high degradability and biogas yield. In summary, AD leads to the overall conversion of food waste into CH_4 and CO_2, and therefore contributes to the reduction of organic matter and recovery of energy from organic carbon in cost-effective manner.

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2.1.2. Ethanol fermentation

Compared to biogas, ethanol production from food waste involves a different approach for waste-to-energy conversion. Various food wastes have been utilized for the production of bio-ethanol, including banana peel (Hammond et al., 1996; Oberoi et al., 2011b; Tewari et al., 1986), sugar beet pulp (Rodríguez et al., 2010), pineapple waste (Ban-Koffi and Han, 1990), grape pomace (Korkie et al., 2002; Rodríguez et al., 2010), potato peel waste (Arapoglou et al., 2010), citrus waste (Boluda-Aguilar et al., 2010; Oberoi et al., 2011a; Pourbafrani et al., 2010) as well as cafeteria food waste (Kim et al., 2011) and household food waste (Matsakas et al., 2014). Due to the complex nature of the lignocellulosic component of food wastes, different pretreatment methods such as acid, alkali, thermal and enzymatic processes have been used in order to increase cellulose digestibility (Arapoglou et al., 2010; Ban-Koffi and Han, 1990; Ma et al., 2011; Oberoi et al., 2011a,b; Singhai et al., 2012; Tewari et al., 1986; Vavouraki et al., 2013). Enzymatic hydrolysis is probably the most common pretreatment method in ethanol production from food waste. Moon et al. (2009) achieved 29.1 g/L ethanol yield from food waste using both carbohydrases and amyloglucosidases. A similar yield (32.2 g/L) was obtained in the study of Uncu and Cekmecelioglu (2011) using food waste treated with amylases. Although the pretreatment can facilitate ethanol production by increasing digestibility of cellulose, the soluble sugars can be degraded forming various inhibitors such as furfural, especially if the treatment is performed at harsh conditions and in the presence of alkali (Matsakas et al., 2014). In most cases, *Saccharomyces cerevisiae* was utilized for fermentation, although Ban-Koffi and Han (1990) also used *Zymomonas mobilis* and Korkie et al. (2002) utilized *Pichia rhodanensis*. *S. cerevisiae* has the disadvantage in that it can only utilize hexose sugars (Balat, 2011), but other fermentative organisms can be used for utilization of pentose sugars for ethanol production. An ethanol yield of 0.43 g ethanol/g TS and 0.31 g ethanol/g TS was obtained for separated hydrolysis and fermentation and simultaneous saccharification and fermentation, respectively (Kim et al., 2011). Thus, an average energy content of 8.3–11.6 kJ/g TS could be estimated for ethanol produced from food waste based on 26.9 MJ/kg energy content of ethanol.

It can be concluded from the literature that AD and ethanol fermentation are considered effective biological processes to convert food waste to energy. The prime advantages of AD include (i) food waste can be co-digested with different substrates in the anaerobic bioreactors, which enables both the waste management and the production of desired products, and (ii) the low cost production of biogas is considered to be vital for meeting future energy demands. However, different factors such as types of reactors, the composition and quality of co-substrates, process control factors (temperature, pH, OLR, HRT), and microbial dynamics contribute to the efficiency of AD process, and must be optimized to achieve maximum benefits from this technology. For the fermentation process, it is feasible to make ethanol from food waste and is more attractive as this technology avoids competition with food crops, reduces food waste and lowers the carbon food print. However, the overall economic viability of the process should still be considered and further studies are required to lower the cost of ethanol production from food waste.

2.2. Thermal and thermochemical technology

2.2.1. Incineration

Incineration is a mature technology that involves the combustion and conversion of waste materials into heat and energy. The heat from the combustion process can be used to operate steam turbines for energy production, or for heat exchangers used to heat up process streams in industry (Autret et al., 2007; Stillman, 1983). Incinerators are able to reduce the volume of solid wastes up to 80–85%, and thus, significantly reduce the necessary volume for disposal. While the combustion of solid wastes is an old technique, its use as a viable waste management strategy is still not fully accepted by some European Member states. The reluctance of some countries to rely on waste incineration is related to toxic air emissions containing dioxins and heavy metals generated from the earlier equipment and technologies (Katami et al., 2004). Thus, air pollution control measures have to be undertaken. Additionally, the incombustible ash usually constitutes a concentrated inorganic waste that has to be disposed of properly. As a result, waste combustion was viewed in a negative light and was even banned in some countries. With the improvement in air emission control systems, a new generation of facilities could be built, which conform to a stricter environmental regulatory regime, significantly decreasing potential human health effects (WHO, 2007). The improvements in combustion technology created favorable conditions for the construction of many new plants in different countries (Grosso et al., 2010). These plants also gained importance with the addition of the energy recovery section. In recovering heat or producing electricity, solid waste combustion was viewed as a part of energy policies, seeking to reduce dependency on fossil fuels.

However, very few studies focusing on direct energy recovery from food waste by incineration are found in the literature. This is due to the fact that food waste alone seems ill-suited for incineration due to high moisture contents and non-combustible components (Mardikar and Niranjan, 1995). Typically, food waste is discarded into the general flow of MSW and converted into heat and energy by incineration. Kim et al. (2013) studied food waste disposal options in Korea with respect to global warming and energy recovery. The food wastes after being dried were discharged with MSW and were burnt at 850 °C to approximately 1,100 °C. Average electricity consumption for drying was estimated to be at 649 kW h, which is equivalent to 27,920 MJ of energy per ton TS of food waste (Kim et al., 2013). The results of incineration revealed that 37.7 kJ of heat from dryer-incineration of 1 g TS of food waste was produced (Kim et al., 2013). The environmental credit was found to be −315 kg of CO_2-eq for dryer-incineration from 1 ton of food waste by electricity, thermal energy generated, and primary materials avoided. It was concluded that dryer-incineration seemed to be the best option for food waste recycling in a metropolitan area in Korea. However, these positive results came from incineration of both MSW and dried food wastes. Energy recovery through incineration of solely food wastes is not always feasible, generally due to the energy loss to evaporate the large water content in these organic wastes. In another study, Caton et al. (2010) investigated energy recovery from post-consumer food waste by direct combustion. They utilized the thermal losses from combustion systems, either through the housing of the systems or expelled through the exhaust, to dehydrate the food garbage. The results showed that energy recovery from wasted food could facilitate cost savings by offsetting traditional fuel use and by reducing disposal costs.

2.2.2. Pyrolysis and gasification

Pyrolysis and gasification are both thermal processes. Pyrolysis converts food waste, in an oxygen-free environment, into bio-oil as the major product along with syngas ($CO + H_2$) and solid bio-char. Gasification converts food waste into a combustible gas mixture by partially oxidizing food waste at high temperature, typically in the range, 800–900 °C (McKendry, 2002). The low calorific value gas produced can be burnt directly or used as a fuel for gas engines and gas turbines. The product gas can be used as a feedstock (syngas) in the production of chemicals (e.g. methanol). Considering the environmental concerns of incineration, pyrolysis, gasification, or both combined appear as alternatives to combustion in food

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Table 3
Food-waste-to-energy conversion processes.

Conversion process	Conversion process conditions	Main products	By-products
Incineration	400–540 °C	Heat, electricity	Ash
Pyrolysis	250–750 °C, absence of oxygen	Char, oil or tar, gas (CO, CH_4, hydrocarbons, H_2, CO_2 (content dependent on process conditions))	Char (use as oil amendment, activated coal or sorbent)
Gasification	350–1800 °C, air, oxygen or steam, 1–30 bar	Gas (CO, CH_4, N_2, H_2, CO_2 (content dependent on process conditions))	Ash
Anaerobic digestion	35–55 °C, anaerobic, reactor size 10–10,000 m^3	Gas (main components CH_4 and CO_2)	Sludge (use as fertilizer after proper treatment)
Ethanol fermentation	30–35 °C, pH 4.5–6.0 anaerobic	Ethanol, CO_2	Animal feed
Hydrothermal carbonization	180–350 °C, 4–45 bar, wet	Hydrochar and gas (main component CO_2)	Crude oil and process water (contains value-added chemicals)

waste treatment. The solid waste gasification and pyrolysis are complex processes composed of a number of physical and chemical interactions that occur at temperatures generally higher than 600 °C, and the exact temperature depends on the reactor type and the waste characteristics, in particular the ash softening and melting temperatures (Demirbas, 2002, 2007; Higman and van der Burgt, 2008; Yaman, 2004). The pyrolysis process degrades the waste to produce energy in the form of syngas, pyrolysis oil or tar (condensable hydrocarbon vapors, that release from solid matrix as gas and liquid in form of mist) and char (the remaining devolatilized solid waste residue) (Knoef, 2005) (Table 3). The gasification process has the merit of producing hydrogen-rich syngas, which can be used as a basic building block for producing valuable products as chemicals and fuels (Garcia et al., 1998; Lee et al., 1999; Young, 2010) under a controlled amount of oxygen. A summary of the products of gasification is given in Table 4.

Gasification has some advantages over traditional incineration technology, mainly related to more acceptable cost and the possibility of coupling the operating conditions (in particular, temperature and equivalence ratio) and the features of the specific reactor (fixed bed, fluidized bed, entrained bed, vertical shaft, moving grate furnace, rotary kiln, plasma reactor) to obtain a syngas suitable for use in different applications (Arena, 2012; Heermann et al., 2001; Young, 2010). Also, the gasification process, when conducted using steam, presents undeniable advantages concerning the formation of dioxins in existing incineration plants. Moreover, these processes can mitigate emissions of air pollutants by using no or low oxygen.

As both gasification and pyrolysis processes work on carbon-based wastes, they are considered appropriate for food wastes. Both produce a syngas composed mainly of CO and H_2 (85%), with a small proportion of CO_2 and CH_4. Pyrolysis produces 75% bio-oil, of which the heating value is around 17 MJ/kg (Digman and Kim, 2008). However, the performance of a waste-to-energy gasification-based process could be affected significantly by the specific properties of the solid waste processed. The most important characteristics of wastes for gasification are elemental composition, lower heating value, ash content (and composition), moisture content, volatile matter content, other contaminants (N, S, Cl, alkalies, heavy metals, etc.), bulk density and size (Zevenhoven-Onderwater et al., 2001). Some of these characteristics are so crucial that most of prevailing gasification technologies generally use pre-processed waste, or refuse-derived fuel as feedstocks rather than the waste as it is (Arena, 2012). As a consequence, there seems to be almost no gasification/pyrolysis processes that have been solely developed for food waste. Ahmed and Gupta (2010) evaluated the pyrolysis and gasification performance in terms of syngas flow rate, hydrogen flow rate, output power, total syngas yield, total hydrogen yield, total energy yield, and apparent thermal efficiency. They found that gasification was more favorable than pyrolysis based on investigated criteria, but longer time was needed to finish the gasification process. The results demonstrate that food waste offers a good potential for solid waste thermal treatment with the specific aim of power generation.

Table 4
Major products of gasification and common health/environmental risks associated with those products (reproduced from Arafat et al., 2013 with permission from Elsevier).

Product	Health/environmental hazards
Carbon dioxide (CO_2)	Green house gas
Methane (CH_4)	Potent green house gas/combustible fuel
Ammonia (NH_3)	Eutrophication
Hydrogen Cyanide (HCN)	Poisonous gas and explosive at high concentrations
Carbon monoxide (CO)	Toxic gas that causes asphyxiation/combustible gas
Hydrogen gas (H_2)	Explosive gas and combustible fuel, can cause asphyxiation

2.2.3. Hydrothermal carbonization

Hydrothermal carbonization (HTC) is one of the thermal conversion technologies attracting increased attention from researchers, especially for waste streams with high moisture content (80–90%). HTC was first experimentally introduced as a means to generate coal from cellulose in 1913 (Libra et al., 2011).

HTC is a wet process that converts food wastes to a valuable, energy-rich resource under autogenous pressures and relatively low temperature (180–350 °C) (Berge et al., 2011; Funke and Ziegler, 2010; Hoekman et al., 2011; Libra et al., 2011; Titirici et al., 2007; Titirici and Antonietti, 2010). A number of studies have recently focused on HTC covering a wide range of feedstocks including lignocellulosic biomass and MSW (Berge et al., 2011; Liu et al., 2012, 2013; Parshetti et al., 2013a,b; Sevilla and Fuertes, 2009). Compared to other waste-to-energy conversion methods using biological processes, HTC has various advantages including smaller treatment footprints, greater waste volume reductions and no process-related odors (Li et al., 2013). Additionally, HTC reaction takes only a few hours compared to days or months needed for biological processes. Furthermore, the high process temperature helps to eliminate pathogens and inactivates other potential organic contaminants (Libra et al., 2011). The process results in the production of a sterile, hygienic, easily stored and transported energy-rich resource. It is also likely that energy can also be recovered from the liquid increasing the energetics of HTC. There is a possibility to recover some of the chemicals from the HTC process water for use/reuse (Berge et al., 2011). Another benefit associated with HTC is related to nutrient recovery from the liquids containing nitrogen species, with the potential of using it as a fertilizer (Li et al., 2013). During HTC, wet feedstocks undergo a series of simultaneous reactions, including hydrolysis, condensation, dehydration, and decarboxylation (Berge et al., 2011; Funke and Ziegler, 2010; Libra et al., 2011; Sevilla and

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Table 5
Hydrochar yield from hydrothermal carbonization of food waste.

Feedstock	Temperature (°C)	Reaction time	Hydrochar yield (%)	% C in hydrochar	Energy content (kJ/g dry solid)	Reference
Rabbit food	250	20 h	43.8	67.6	29.1	Berge et al. (2011)
	250	5 d	30–60	45–75	25–35	Lu et al. (2012)
Dog food	234–295	150 min	55–66	56–58	26	Hwang et al. (2012)
Sweet corn	250	96 h	50–96	69–90	11	Lu and Berge (2014)
Peanut shell	300	30 min	50.1	NR	NR	Huff et al. (2014)
Distiller's grain	190–210	0.5–2 h	30.2–45.6	39.8–59.3	29.66	Heilmann et al. (2011)
Brewer's spent grain	200–240	14 h	47.5–51.1	67.5–67.6	29.9–31.8	Poerschmann et al. (2014)
Orange waste	300	30 min	37.5	62	NR	Pellera et al. (2012)
Olive pomace	300	30 min	37.5	71.1	NR	Pellera et al. (2012)
Grape pomace	175–275	10–60 min	46.5–61.1	65–75	24.32–28.31	Pala et al. (2014)
Restaurant food waste	225–275	96 h	45–95	68.1–78.6	33.57	Li et al. (2013)
Restaurant food waste	150–350	20 min	36–68	44–65	15–26.9	Kaushik et al. (2014)

NR not reported.

Fuertes, 2009; Titirici et al., 2007). A result of this process is the formation of a highly carbonized and energy densified material (often termed hydrochar) that has been reported to have composition equivalent to that of lignite coal (Berge et al., 2011). The surface functionalization patterns of the generated char make it amendable to beneficial end-use applications such as an adsorbent for harmful pollutants (Liu et al., 2010; Parshetti et al., 2014), feedstock for carbon fuel cells (Cao et al., 2007; Paraknowitsch et al., 2009), and soil amendment (similar to char from pyrolysis/gasification) (Spokas and Reicosky, 2009).

HTC of food waste has been reported with different substrates including rabbit food (Berge et al., 2011; Goto et al., 2004; Lu et al., 2012), dog food (Hwang et al., 2012), fish meat (Kang et al., 2001), rice bran (Sugano et al., 2012), wheat bran (Reisinger et al., 2013), tofu waste (Tian et al., 2012), sweet corn (Lu and Berge, 2014), peanut shell (Huff et al., 2014), eggshell (Wu et al., 2013), orange waste (Pellera et al., 2012), grape, sweet potato and pomelo peels (Wu et al., 2013), sugar beet pulp (Cao et al., 2013), grape pomace (Pala et al., 2014), olive pomace (Pellera et al., 2012), distiller's grain (Heilmann et al., 2011), brewer's spent grain (Poerschmann et al., 2014), leftover food (Busch et al., 2013; Wiedner et al., 2013) and restaurant food waste (Kaushik et al., 2014; Li et al., 2013; Ren et al., 2006). These experiments were conducted at different operating conditions at the temperature range of 200–350 °C over a time duration of 0.2–120 h. The results demonstrate that HTC of model food wastes is beneficial, resulting in the production of hydrochar that has high carbon (45–93% of initial carbon) and energy (15–30 kJ/g dry solids) contents. The hydrochar yields from different food wastes were summarized in Table 5. Lu et al. (2012) suggested that the energy derived from hydrochar resulting from HTC of model food waste may be greater than that expected during incineration. Li et al. (2013) used food wastes collected from local restaurants as feedstocks for HTC. They found that a significant fraction (>70%) of the carbon in the initial substrate remained bound within the solid-phase over the 96-h reaction period. This observation is consistent with carbonization studies reported in the literature associated with model food wastes (e.g., rabbit and dog food) and other feedstocks, such as cellulose, xylose, and glucose (Goto et al., 2004; Hwang et al., 2012; Kang et al., 2012; Lu et al., 2012; Sevilla and Fuertes, 2009). Smaller fractions of carbon were transferred to the liquid (10–40%) and gas-phases (<10%), also consistent with previous studies (Berge et al., 2011; Hoekman et al., 2011; Lu et al., 2012). HTC is particularly beneficial for food waste as the intensive energy for drying can be avoided. On the other hand, HTC is seen as an efficient process for carbon sequestration to mitigate climate changes compared to other processes. When food waste is anaerobically digested or fermented, some of the original carbon in the substrate is converted into CO_2 and lost to the atmosphere. With HTC, however, most of the original carbon present in food waste remains integrated in the final hydrochar product (Titirici et al., 2007).

3. Concluding remarks and future directions

In the light of rapidly rising costs associated with energy supply and waste disposal and increasing public concerns with environmental quality, the conversion of food wastes to energy is becoming an environmentally benign and economically attractive practice. Food waste compositions vary significantly based on their sources. Some important characteristics of food wastes that have been reported include a moisture content of 74–90%, volatile solids to total solids ratio of 0.8–0.97, and carbon to nitrogen ratio of 14.7–36.4 (Zhang et al., 2007). Because of relatively high moisture contents of food waste, common thermal treatments such as incineration, pyrolysis and gasification are considered energetically unfavorable. Besides the loss of organic matter and nitrogen, various environmental pollution problems which may arise as a result of the absence of proper air pollution control measures (e.g. emissions of toxic air pollutants) associated with incineration provided a strong impetus for the search for alternative, environment-friendly methods of handling food wastes. Pyrolysis and gasification processes are favorable in terms of reducing CO_2 emissions and operation costs compared to incineration. However, the utilization of food waste in this area is not devoid of challenges, due to variability of waste compositions which significantly influence the processes. The key issues are the high moisture contents, lower heating values and highly heterogeneous nature of food wastes, which result in technical and economic problems while using pyrolysis and gasification. Alternatively, food waste can be converted to ethanol by fermentation with ethanol producing microorganisms such as *S. cerevisiae*. However, a pretreatment technique is required to hydrolyze the food waste and produce fermentable sugars, which contributes to increased costs of the whole process (Matsakas et al., 2014). Additionally, various inhibitors can be formed during the pretreatment, which tend to inhibit the microorganisms activity in the fermentation process. Other technological options that merit consideration are AD and HTC. AD is performed by a consortium of microorganisms which break down the organic matter into biogas (mainly CH_4) in the absence of oxygen. Biogas can be burned for heat and electricity production. HTC converts food waste into hydrochar and crude oil which can be considered as easily stored energy-rich resources. AD has various disadvantages such as the need for large treatment footprints, little volume reduction of wastes and process-related odors. Another disadvantage of AD is that anaerobic bacteria are sensitive to changes in process conditions such as pH, temperature, salts and toxic materials generated during the reactions, requiring stringent

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Table 6
Overall comparison of food-waste-to-enery conversion technologies in terms of environmental and energy-economic and health aspects.

Technologies		Anaerobic digestion	Ethanol fermentation	Incineration	Pyrolysis/ gasification	Hydrothermal carbonization
Environmental aspects	Greenhouse effect	++++	++++	+	+++	+++++
	Odor problem	+	++	+++++	+++++	+++++
	Air/water pollution	++++	+++++	+	+++	+++++
Energy-economic and health aspects	Human health	++	++++	+	+	+++++
	Process speed	+	+++	++++	++++	+++++
	Energy production yield	+	+++	+++	+++	+++++
	Relative cost	++	++	++	+++	+++

+ Very poor, ++ Poor, +++ Moderate, ++++ Good, +++++ Very good.

process control and optimization operations (Khalid et al., 2011). HTC requires the higher reaction temperature (180–350 °C) compared to AD (35–55 °C) for the conversion of food waste to useful products. However, this process heat requirement can be offset by the energy generated from HTC products as well as byproducts from process water. In HTC, the high process temperature eliminates pathogens and inactivates other potential organic contaminants (Libra et al., 2011). Finally, the reaction time of HTC (e.g. typically less than 60 min) is much shorter than AD (e.g. generally longer than 20 days), which considerably improves the processing of food wastes on a continual basis and increases the throughput of products.

An overall summary of all energy conversion technologies in terms of environmental and energy-economic and health aspects is given in Table 6. Although the HTC process for food waste has several advantages over other energy conversion technologies, there still remain some challenges and questions that should draw scientific attention for future directions in this research. The key research questions are (a) can we find a proper catalyst to lower the reaction temperature and pressure, especially for the high-temperature HTC process?; (b) is it possible to digest food waste biomass by HTC to produce functional carbonaceous hydrochar materials for their possible energy applications?; (c) what is the detailed chemical mechanism of low-temperature HTC & high-temperature HTC as applicable to food wastes? and (d) how can we rationally design the HTC process to control the detailed components of the hydrochar materials and liquid products? Since enzymatic pretreatment has recently been found to be beneficial to increase the yield of these products, it would be of scientific interest to further explore this enzymatic-assisted HTC process for production of fine chemicals from food waste. Solving these challenges and problems in the future will further facilitate and strengthen the capability for a rational design of a variety of hydrochar materials and extended practical applications such as (1) CO_2 sequestration, (2) energy generation (by co-combusting with coal), (3) catalyst/adsorbent, (4) electric applications (Lithium ion batteries), and (5) soil amendments (soil nutrient cycles).

Biological treatment methods possess advantages such as simplicity and low capital cost. However, it has the inherent disadvantages of a long treatment time and the possibility of inhibition of bacteria due to exposure to contaminants in food waste. Among thermal and thermochemical techniques, HTC is an attractive option for converting raw food waste into useful products such as hydrochar, oil and other energy-rich compounds. However, a detailed techno-economic analysis has to be done to study the feasibility of using HTC for a large-scale operation. Finally, a systematic multi-disciplinary approach is needed with inputs from experts in the field to derive both short and long-term benefits in terms of energy and material recovery from the conversion of food wastes.

Acknowledgments

The authors are thankful to the National Environment Agency (Environment Technology Research Programme Grant) and the National University of Singapore for the financial support extended to this study.

References

Ahmed, I.I., Gupta, A.K., 2010. Pyrolysis and gasification of food waste: syngas characteristics and char gasification kinetics. Appl. Energy 87 (1), 101–108.

Alvarez, R., Lidén, G., 2008. Semi-continuous co-digestion of solid slaughterhouse waste, manure, and fruit and vegetable waste. Renew. Energy 33 (4), 726–734.

Amoo, O.M., Fagbenle, R.L., 2013. Renewable municipal solid waste pathways for energy generation and sustainable development in the Nigerian context. Int. J. Energy Environ. Eng. 4, 42–59.

Arafat, H.A., Jijakli, K., Ahsan, A., 2013. Environmental performance and energy recovery potential of five processes for municipal solid waste treatment. J. Clean. Prod.. http://dx.doi.org/10.1016/j.jclepro.2013.11.071.

Arapoglou, D., Varzakas, T., Vlyssides, A., Israilides, C., 2010. Ethanol production from potato peel waste (PPW). Waste Manage. 30 (10), 1898–1902.

Arena, U., 2012. Process and technological aspects of municipal solid waste gasification. A review. Waste Manage. 32 (4), 625–639.

Autret, E., Berthier, F., Luszezanec, A., Nicolas, F., 2007. Incineration of municipal and assimilated wastes in France: assessment of latest energy and material recovery performances. J. Hazard. Mater. 139 (3), 569–574.

Balat, M., 2011. Production of bioethanol from lignocellulosic materials via the biochemical pathway: a review. Energy Convers. Manage. 52 (2), 858–875.

Ban-Koffi, L., Han, Y.W., 1990. Alcohol production from pineapple waste. World J. Microbiol. Biotechnol. 6, 281–284.

Banks, C.J., Chesshire, M., Heaven, S., Arnold, R., 2011. Anaerobic digestion of source-segregated domestic food waste: performance assessment by mass and energy balance. Bioresour. Technol. 102, 612–620.

Beccari, M., Majone, M., Petrangeli Papini, M., Torrisi, L., 2001. Enhancement of anaerobic treatability of olive oil mill effluents by addition of $Ca(OH)_2$ and bentonite without intermediate solid/liquid separation. Water Sci. Technol. 43 (11), 275–282.

Berge, N.D., Ro, K.S., Mao, J., Flora, J.R., Chappell, M.A., Bae, S., 2011. Hydrothermal carbonization of municipal waste streams. Environ. Sci. Technol. 45 (13), 5696–5703.

Boluda-Aguilar, M., Garcia-Vidal, L., Gonzalez-Castaneda Fdel, P., Lopez-Gomez, A., 2010. Mandarin peel wastes pretreatment with steam explosion for bioethanol production. Bioresour. Technol. 101 (10), 3506–3513.

Bouallagui, H., Ben Cheikh, R., Marouani, L., Hamdi, M., 2003. Mesophilic biogas production from fruit and vegetable waste in a tubular digester. Bioresour. Technol. 86, 85–89.

Bouallagui, H., Touhami, Y., Ben Cheikh, R., Hamdi, M., 2005. Bioreactor performance in anaerobic digestion of fruit and vegetable wastes. Process Biochem. 40 (3–4), 989–995.

Bouallagui, H., Rachdi, B., Gannoun, H., Hamdi, M., 2009. Mesophilic and thermophilic anaerobic co-digestion of abattoir wastewater and fruit and vegetable waste in anaerobic sequencing batch reactors. Biodegradation 20 (3), 401–409.

Busch, D., Stark, A., Kammann, C.I., Glaser, B., 2013. Genotoxic and phytotoxic risk assessment of fresh and treated hydrochar from hydrothermal carbonization compared to biochar from pyrolysis. Ecotoxicol. Environ. Saf. 97, 59–66.

Cao, D., Sun, Y., Wang, G., 2007. Direct carbon fuel cell: fundamentals and recent developments. J. Power Sources 167 (2), 250–257.

Cao, X., Ro, K.S., Libra, J.A., Kammann, C.I., Lima, I., Berge, N., Li, L., Li, Y., Chen, N., Yang, J., Deng, B., Mao, J., 2013. Effects of biomass types and carbonization conditions on the chemical characteristics of hydrochars. J. Agric. Food Chem. 61, 9401–9411.

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Castillo, M.E.F., Cristancho, D.E., Arellano, A.V., 2006. Study of the operational conditions for anaerobic digestion of urban solid wastes. Waste Manage. 26 (5), 546–556.

Caton, P.A., Carr, M.A., Kim, S.S., Beautyman, M.J., 2010. Energy recovery from waste food by combustion or gasification with the potential for regenerative dehydration: a case study. Energy Convers. Manage. 51 (6), 1157–1169.

Chanakya, H.N., Ramachandra, T.V., Vijayachamundeeswari, M., 2007. Resource recovery potential from secondary components of segregated municipal solid wastes. Environ. Monit. Assess. 135 (1–3), 119–127.

Chen, Y., Cheng, J.J., Creamer, K.S., 2008. Inhibition of anaerobic digestion process: a review. Bioresour. Technol. 99 (10), 4044–4064.

Demirbas, A., 2002. Gaseous products from biomass by pyrolysis and gasification: effects of catalyst on hydrogen yield. Energy Convers. Manage. 43, 897–909.

Demirbas, A., 2007. Effect of temperature on pyrolysis products from biomass. Energy Sources Part A 29 (4), 329–336.

Digman, B., Kim, D.-S., 2008. Review: alternative energy from food processing wastes. Environ. Prog. 27 (4), 524–537.

European Commission, 2010. Final Report–Preparatory Study on Food Waste across EU27. Bio Intelligence Service, Paris.

FAO-Food and Agriculture Organization, 2009. How to Feed the World in 2050. Food and Agriculture Organization.

FAO-Food and Agriculture Organization, 2011. Global Food Losses and Food Waste–Extent, Causes and Prevention. Food and Agriculture Organization, Rome.

Forster-Carneiro, T., Perez, M., Romero, L.I., 2008a. Influence of total solid and inoculum contents on performance of anaerobic reactors treating food waste. Bioresour. Technol. 99 (15), 6994–7002.

Forster-Carneiro, T., Perez, M., Romero, L.I., 2008b. Thermophilic anaerobic digestion of source-sorted organic fraction of municipal solid waste. Bioresour. Technol. 99 (15), 6763–6770.

Fountoulakis, M.S., Drakopoulou, S., Terzakis, S., Georgaki, E., Manios, T., 2008. Potential for methane production from typical Mediterranean agro-industrial by-products. Biomass Bioenergy 32 (2), 155–161.

Funke, A., Ziegler, F., 2010. Hydrothermal carbonization of biomass: a summary and discussion of chemical mechanisms for process engineering. Biofuels Bioprod. Bioref. 4 (2), 160–177.

Garcia, L., Salvador, M.L., Bilbao, R., Arauzo, J., 1998. Influence of calcination and reduction conditions on the catalyst performance in the pyrolysis process of biomass. Energy Fuel 12, 139–143.

Gómez, X., Cuetos, M.J., Cara, J., Morán, A., García, A.I., 2006. Anaerobic co-digestion of primary sludge and the fruit and vegetable fraction of the municipal solid wastes. Renew. Energy 31 (12), 2017–2024.

Goto, M., Obuchi, R., Hirose, T., Sakaki, T., Shibata, M., 2004. Hydrothermal conversion of municipal organic waste into resources. Bioresour. Technol. 93 (3), 279–284.

Grosso, M., Motta, A., Rigamonti, L., 2010. Efficiency of energy recovery from waste incineration, in the light of the new Waste Framework Directive. Waste Manage. 30 (7), 1238–1243.

Guermoud, N., Ouadjnia, F., Abdelmalek, F., Taleb, F., Addou, A., 2009. Municipal solid waste in Mostaganem city (Western Algeria). Waste Manage. 29 (2), 896–902.

Hammond, J.B., Egg, R., Diggins, D., Coble, C.G., 1996. Alcohol from bananas. Bioresour. Technol. 56, 125–130.

Heermann, C., Schwager, F.J., Whiting, K.J., 2001. Pyrolysis & Gasification of Waste. A Worldwide Technology & Business Review, second ed. Juniper Consultancy Services Ltd..

Heilmann, S.M., Jader, L.R., Sadowsky, M.J., Schendel, F.J., Keitz, M.G.V., Valentas, K.J., 2011. Hydrothermal carbonization of distiller's grains. Biomass Bioenergy 35, 2526–2533.

Higman, C., van der Burgt, M., 2008. Gasification, second ed. Gulf Professional Publishing, Oxford, UK.

Hoekman, S.K., Broch, A., Robbins, C., 2011. Hydrothermal carbonization (HTC) of lignocellulosic biomass. Energy Fuel 25 (4), 1802–1810.

Huff, M.D., Kumar, S., Lee, J.W., 2014. Comparative analysis of pinewood, peanut shell, and bamboo biomass derived biochars produced via hydrothermal conversion and pyrolysis. J. Environ. Manage. 146, 303–308.

Hwang, I.H., Aoyama, H., Matsuto, T., Nakagishi, T., Matsuo, T., 2012. Recovery of solid fuel from municipal solid waste by hydrothermal treatment using subcritical water. Waste Manage. 32 (3), 410–416.

IPCC (Intergovernmental Panel on Climate Change), 2006. In: Eggleston, S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (Eds.), Waste Generation, Composition and Management Data (Chapter 2).

Izumi, K., Okishio, Y.K., Niwa, C., Yamamoto, S., Toda, T., 2010. Effects of particle size on anaerobic digestion of food waste. Int. Bio-deteriro. Biodegr. 64, 601–608.

Joshi, V.K., 2002. Food processing industries' waste: opportunities, technologies, challenges and future strategies. In: Arora, J.K., Marwaha, S.S., Grover, R. (Eds.), Biotechnology in Agriculture and Environment. Asiatech Publishers, New Delhi, pp. 129–148.

Kabouris, J.C., Tezel, U., Pavlostathis, S.G., Engelmann, M., Dulaney, J., Gillette, R.A., Todd, A.C., 2009. Methane recovery from the anaerobic codigestion of municipal sludge and FOG. Bioresour. Technol. 100 (15), 3701–3705.

Kang, K., Quitain, A.T., Daimon, H., Noda, R., Goto, N., Hu, H.Y., Fujie, K., 2001. Optimization of amino acids production from waste fish entrails by hydrolysis in sub- and supercritical water. Can. J. Chem. Eng. 79 (1), 65–70.

Kang, S., Li, X., Fan, J., Chang, J., 2012. Characterization of hydrochars produced by hydrothermal carbonization of lignin, cellulose, d-xylose, and wood meal. Ind. Eng. Chem. Res. 51 (26), 9023–9031.

Karagiannidis, A., Perkoulidis, G., 2009. A multi-criteria ranking of different technologies for the anaerobic digestion for energy recovery of the organic fraction of municipal solid wastes. Bioresour. Technol. 100 (8), 2355–2360.

Katami, T., Yasuhara, A., Shibamoto, T., 2004. Formation of dioxins from incineration of foods found in domestic garbage. Environ. Sci. Technol. 38, 1062–1065.

Kaushik, R., Parshetti, G., Liu, Z., Balasubramanian, R., 2014. Enzyme-assisted hydrothermal treatment of food waste for co-production of hydrochar and bio-oil. Bioresour. Technol. 168, 267–274.

Khalid, A., Arshad, M., Anjum, M., Mahmood, T., Dawson, L., 2011. The anaerobic digestion of solid organic waste. Waste Manage. 31, 1737–1744.

Kim, H.J., Kim, S.H., Choi, Y.G., Kim, G.D., Chung, T.H., 2006a. Effect of enzymatic pretreatment on acid fermentation of food waste. J. Chem. Technol. Biotechnol. 81 (6), 974–980.

Kim, J.K., Oh, B.R., Chun, Y.N., Kim, S.W., 2006b. Effects of temperature and hydraulic retention time on anaerobic digestion of food waste. J. Biosci. Bioeng. 102 (4), 328–332.

Kim, J.H., Lee, J.C., Pak, D., 2011. Feasibility of producing ethanol from food waste. Waste Manage. 31 (9–10), 2121–2125.

Kim, M.H., Song, H.B., Song, Y., Jeong, I.T., Kim, J.W., 2013. Evaluation of food waste disposal options in terms of global warming and energy recovery: Korea. Int. J. Energy Environ. Eng. 4, 1–12.

Kivaisi, A.K., Eliapenda, S., 1994. Pretreatment of bagasse and coconut fibres for enhanced anaerobic degradation by rumen microorganisms. Renew. Energy 5, 791–795.

Knoef, H., 2005. Practical aspects of biomass gasification. In: Knoef, H. (Ed.), Handbook Biomass Gasification. BTG-Biomass Technology Group. Enschede, The Netherlands. ISBN: 90-810068-1-9.

Korkie, L.J., Janse, B.J.H., Viljoen-Bloom, M., 2002. Utilizing grape pomace for ethanol production. S. Afr. J. Enol. Viticult. 23, 31–36.

Kosseva, M.R., 2009. Processing of food wastes. In: Taylor, S.L. (Ed.), Advances in Food and Nutrition Research, vol. 58, pp. 57–136.

Kosseva, M.R., 2011. Management and processing of food wastes. In: Reference Module in Earth Systems and Environmental Sciences Comprehensive Biotechnology, second ed., pp. 557–593.

Lee, S.W., Kim, S.B., Lee, K.W., Choi, C.S., 1999. Catalytic gasification of rice straw at low temperature. Environ. Eng. Res. 4, 293–300.

Li, H., Kim, N.J., Jiang, M., Kang, J.W., Chang, H.N., 2009. Simultaneous saccharification and fermentation of lignocellulosic residues pretreated with phosphoric acid–acetone for bioethanol production. Bioresour. Technol. 100 (13), 3245–3251.

Li, L., Diederick, R., Flora, J.R., Berge, N.D., 2013. Hydrothermal carbonization of food waste and associated packaging materials for energy source generation. Waste Manage. 33 (11), 2478–2492.

Libra, J.A., Ro, K.S., Kammann, C., Funke, A., Berge, N.D., Neubauer, Y., Titirici, M.-M., Führer, C., Bens, O., Kern, J., Emmerich, K.-H., 2011. Hydrothermal carbonization of biomass residuals: a comparative review of the chemistry, processes and applications of wet and dry pyrolysis. Biofuels 2, 71–106.

Lin, C.S.K., Pfaltzgraff, L.A., Herrero-Davila, L., Mubofu, E.B., Abderrahim, S., Clark, J.H., Koutinas, A.A., Kopsahelis, N., Stamatelatou, K., Dickson, F., Thankappan, S., Mohamed, Z., Brocklesby, R., Luque, R., 2013. Food waste as a valuable resource for the production of chemicals, materials and fuels. Current situation and global perspective. Energy Environ. Sci. 6, 426–464.

Linke, B., 2006. Kinetic study of thermophilic anaerobic digestion of solid wastes from potato processing. Biomass Bioenergy 30 (10), 892–896.

Liu, Z., Zhang, F.-S., Wu, J., 2010. Characterization and application of chars produced from pinewood pyrolysis and hydrothermal treatment. Fuel 89 (2), 510–514.

Liu, Z., Quek, A., Kent Hoekman, S., Srinivasan, M.P., Balasubramanian, R., 2012. Thermogravimetric investigation of hydrochar-lignite co-combustion. Bioresour. Technol. 123, 646–652.

Liu, Z., Quek, A., Kent Hoekman, S., Balasubramanian, R., 2013. Production of solid biochar fuel from waste biomass by hydrothermal carbonization. Fuel 103, 943–949.

Lu, X., Berge, N.D., 2014. Influence of feedstock chemical composition on product formation and characteristics derived from the hydrothermal carbonization of mixed feedstocks. Bioresour. Technol. 166, 120–131.

Lu, X., Jordan, B., Berge, N.D., 2012. Thermal conversion of municipal solid waste via hydrothermal carbonization: comparison of carbonization products to products from current waste management techniques. Waste Manage. 32 (7), 1353–1365.

Ma, J., Duong, T.H., Smits, M., Verstraete, W., Carballa, M., 2011. Enhanced biomethanation of kitchen waste by different pre-treatments. Bioresour. Technol. 102 (2), 592–599.

Mardikar, S.H., Niranjan, K., 1995. Food processing and the environment. Environ. Manage. Health 6 (3), 23–26.

Marin, J., Kennedy, K.J., Eskicioglu, C., 2010. Effect of microwave irradiation on anaerobic degradability of model kitchen waste. Waste Manage. 30, 1772–1779.

Marwaha, S.S., Arora, J.K., 2000. Food Processing: Biotechnological Applications. Asiatech Publishers, New Delhi.

Matsakas, L., Kekos, D., Loizidou, M., Christakopoulos, P., 2014. Utilization of household food waste for the production of ethanol at high dry material content. Biotechnol. Biofuels 7, 4–13.

McKendry, P., 2002. Energy production from biomass (Part 2): conversion technologies. Bioresour. Technol. 83, 47–54.

Moon, H.C., Song, I.S., Kim, J.C., Shirai, Y., Lee, D.H., Kim, J.K., Chung, S.O., Kim, D.H., Oh, K.K., Cho, Y.S., 2009. Enzymatic hydrolysis of food waste and ethanol fermentation. Int. J. Energy Res. 33, 164–172.

Please cite this article in press as: Pham, T.P.T., et al. Food-waste-to-energy conversion technologies: Current status and future directions. Waste Management (2014), http://dx.doi.org/10.1016/j.wasman.2014.12.004

Morris, J., 1996. Recycling versus incineration: an energy conservation analysis. J. Hazard. Mater. 47, 277–293.

Murphy, J.D., McKeogh, E., Kiely, G., 2004. Technical/economic/environmental analysis of biogas utilisation. Appl. Energy 77 (4), 407–427.

Nakamura, Y., Sawada, T., 2003. Ethanol production from artificial domestic household waste solubilized by steam explosion. Biotechnol. Bioprocess Eng. 8, 205–209.

NEA Waste Statistics and Overall Recycling, 2012. <http://app2.nea.gov.sg/energy-waste/waste-management/waste-statistics-and-overall-recycling>.

Neves, L., Ribeiro, R., Oliveira, R., Alves, M.M., 2006. Enhancement of methane production from barley waste. Biomass Bioenergy 30 (6), 599–603.

NRDC (National Resources Defense Council), 2012. Wasted: How America is losing up to 40 percent of its Food from Farm to Fork to Landfill.

Oberoi, H.S., Vadlani, P.V., Nanjundaswamy, A., Bansal, S., Singh, S., Kaur, S., Babbar, N., 2011a. Enhanced ethanol production from Kinnow mandarin (*Citrus reticulata*) waste via a statistically optimized simultaneous saccharification and fermentation process. Bioresour. Technol. 102 (2), 1593–1601.

Oberoi, H.S., Vadlani, P.V., Saida, L., Bansal, S., Hughes, J.D., 2011b. Ethanol production from banana peels using statistically optimized simultaneous saccharification and fermentation process. Waste Manage. 31 (7), 1576–1584.

Oelofse, S.H.H., Nahman, A., 2013. Estimating the magnitude of food waste generated in South Africa. Waste Manage. Res. 31 (1), 80–86.

Pala, M., Kantarli, I.C., Buyukisik, H.B., Yanik, J., 2014. Hydrothermal carbonization and torrefaction of grape pomace: a comparative evaluation. Bioresour. Technol. 161, 255–262.

Paraknowitsch, J.P., Thomas, A., Antonietti, M., 2009. Carbon colloids prepared by hydrothermal carbonization as efficient fuel for indirect carbon fuel cells. Chem. Mater. 21, 1170–1172.

Parawira, W., Murto, M., Zvauya, R., Mattiasson, B., 2004. Anaerobic batch digestion of solid potato waste alone and in combination with sugar beet leaves. Renew. Energy 29 (11), 1811–1823.

Parshetti, G.K., Kent Hoekman, S., Balasubramanian, R., 2013a. Chemical, structural and combustion characteristics of carbonaceous products obtained by hydrothermal carbonization of palm empty fruit bunches. Bioresour. Technol. 135, 683–689.

Parshetti, G.K., Liu, Z., Jain, A., Srinivasan, M.P., Balasubramanian, R., 2013b. Hydrothermal carbonization of sewage sludge for energy production with coal. Fuel 111, 201–210.

Parshetti, G.K., Chowdhury, S., Balasubramanian, R., 2014. Hydrothermal conversion of urban food waste to chars for removal of textile dyes from contaminated waters. Bioresour. Technol. 161, 310–319.

Pellera, F.-M., Giannis, A., Kalderis, D., Anastasiadou, K., Stegmann, R., Wang, J.-Y., Gidarakos, E., 2012. Adsorption of Cu(II) ions from aqueous solutions on biochars prepared from agricultural by-products. J. Environ. Manage. 96, 35–42.

Pfaltzgraff, L.A., De Bruyn, M., Cooper, E.C., Budarin, V., Clark, J.H., 2013. Food waste biomass: a resource for high-value chemicals. Green Chem. 15, 307–314.

Poerschmann, J., Weiner, B., Wedwitschka, H., Baskyr, I., Koehler, R., Kopinke, F.-D., 2014. Characterization of biocoals and dissolved organic matter phases obtained upon hydrothermal carbonization of brewer's spent grain. Bioresour. Technol. 164, 162–169.

Pourbafrani, M., Forgacs, G., Horvath, I.S., Niklasson, C., Taherzadeh, M.J., 2010. Production of biofuels, limonene and pectin from citrus wastes. Bioresour. Technol. 101 (11), 4246–4250.

Reisinger, M., Tirpanalan, Ö., Prückler, M., Huber, F., Kneifel, W., Novalin, S., 2013. Wheat bran biorefinery – a detailed investigation on hydrothermal and enzymatic treatment. Bioresour. Technol. 144, 179–185.

Ren, L.-H., Nie, Y.-F., Liu, J.-G., Jin, Y.-Y., Sun, L., 2006. Impact of hydrothermal process on the nutrient ingredients of restaurant garbabe. J. Environ. Sci. 18 (5), 1012–1019.

Rodríguez, L.A., Toro, M.E., Vazquez, F., Correa-Daneri, M.L., Gouiric, S.C., Vallejo, M.D., 2010. Bioethanol production from grape and sugar beet pomaces by solid-state fermentation. Int. J. Hydrogen Energy 35 (11), 5914–5917.

Sawayama, S., Inoue, S., Minowa, T., Tsukahara, K., Ogi, T., 1997. Thermochemical liquidization and anaerobic treatment of kitchen garbage. J. Ferment. Bioeng. 83 (5), 451–455.

Sevilla, M., Fuertes, A.B., 2009. The production of carbon materials by hydrothermal carbonization of cellulose. Carbon 47 (9), 2281–2289.

Singhai, Y., Bansal, S.K., Singh, R., 2012. Evaluation of biogas production from solid waste using pretreatment method in anaerobic condition. Int. J. Emerg. Sci. 2 (3), 405–414.

Spokas, K.A., Reicosky, D.C., 2009. Impacts of sixteen different biochars on soil greenhouse gas production. Ann. Environ. Sci. 3, 179–193.

Stillman, G.I., 1983. Municipal solid waste (garbage): problems and benefits. Ann. N. Y. Acad. Sci. 403 (1), 1–26.

Sugano, M., Yuze, M., Komatsu, A., Enomoto, T., Kakuta, Y., Hirano, K., 2012. Extraction of valuable compounds from hydrothermally reacted rice bran and wheat bran. Waste Biomass Valorizat. 3 (4), 381–393.

Taherzadeh, M.J., Karimi, K., 2008. Pretreatment of lignocellulosic wastes to improve ethanol and biogas production: a review. Int. J. Mol. Sci. 9 (9), 1621–1651.

Tewari, H.K., Marwaha, S.S., Rupal, K., 1986. Ethanol from banana peels. Agric. Wastes 16, 135–146.

Tian, Y., Kumabe, K., Matsumoto, K., Takeuchi, H., Xie, Y., Hasegawa, T., 2012. Hydrolysis behavior of tofu waste in hot compressed waster. Biomass Bioenergy 39, 112–119.

Titirici, M.-M., Antonietti, M., 2010. Chemistry and materials options of sustainable carbon materials made by hydrothermal carbonization. Chem. Soc. Rev. 39 (1), 103–116.

Titirici, M.-M., Thomas, A., Antonietti, M., 2007. Back in the black: hydrothermal carbonization of plant material as an efficient chemical process to treat the CO_2 problem? New J. Chem. 31 (6), 787–789.

Uncu, O.N., Cekmecelioglu, D., 2011. Cost-effective approach to ethanol production and optimization by response surface methodology. Waste Manage. 31, 636–643.

Vavouraki, A.I., Angelis, E.M., Kornaros, M., 2013. Optimization of thermo-chemical hydrolysis of kitchen wastes. Waste Manage. 33 (3), 740–745.

WHO, 2007. Population, Health and Waste Management: Scientific Data and Policy Options. Report of a WHO Workshop, 29–30 March 2007, Rome, Italy.

Wiedner, K., Rumpel, C., Steiner, C., Pozzi, A., Maas, R., Glaser, B., 2013. Chemical evaluation of chars produced by thermochemical conversion (gasification, pyrolysis and hydrothermal carbonization) of agro-industrial biomass on a commercial scale. Biomass Bioenergy 59, 264–278.

Wu, S.-C., Tsou, H.-K., Hsu, H.-C., Hsu, S.-K., Liou, S.-P., Ho, W.-F., 2013. A hydrothermal synthesis of eggshell and fruit waste extract to produce nanosized hydroxyapatite. Ceram. Int. 39, 8183–8188.

Yaman, S., 2004. Pyrolysis of biomass to produce fuels and chemical feedstocks. Energy Convers. Manage. 45 (5), 651–671.

Yan, B.H., Selvam, A., Wong, J.W.C., 2014. Application of rumen microbes to enhance food waste hydrolysis in acidogenic leach-bed reactors. Bioresour. Technol. 168, 64–71.

Young, G., 2010. Municipal Solid Waste to Energy Conversion Processes: Economic, Technical and Renewable Comparisons. J. Wiley & Sons Inc.

Zevenhoven-Onderwater, M., Backman, R., Skrifvars, B.-J., Hupa, M., 2001. The ash chemistry in fluidised bed gasification of biomass fuels. Part I: predicting the chemistry of melting ashes and ash-bed material interaction. Fuel 80, 1489–1502.

Zhang, R., El-Mashad, H.M., Hartman, K., Wang, F., Liu, G., Choate, C., Gamble, P., 2007. Characterization of food waste as feedstock for anaerobic digestion. Bioresour. Technol. 98 (4), 929–935.

Zhu, B., Gikas, P., Zhang, R., Lord, J., Jenkins, B., Li, X., 2009. Characteristics and biogas production potential of municipal solid wastes pretreated with a rotary drum reactor. Bioresour. Technol. 100 (3), 1122–1129.